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PROJECT ADMINISTRATION DATA SHEET

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Project No. E-16-632 (R-5907-0A0) GTRC/~~GIT~~ XXX DATE 3 / 13 / 85

Project Director: Dr. B. T. Zinn School/~~Lab~~ XXX AE

Sponsor: AFOSR Bolling AFB, DC

Type Agreement: Grant 84-0082 Amendment A

Award Period: From 2/1/85 To 1/31/86 (Performance) 1/31/86 (Reports)

Sponsor Amount:

	This Change	Total to Date
Estimated:	$	$
Funded:	$ 104,423	$ 199,134

Cost Sharing Amount: $ 11,789 Cost Sharing No: E-16-325 (F-5907-0A0)

Title: Investigation of the Flame - Acoustic Wave Interaction During Axial Solid Rocket Instabilities

ADMINISTRATIVE DATA

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Defense Priority Rating: ______ Military Security Classification: N/A

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Equipment: Title vests with GIT - See page 2 of Grant Amendment

COMMENTS:

This amendment adds $104,423 through 1/31/86 to Grant No. AFOSR-84-0082. Cost share amount of $11,789 is required. This is a follow on to E-16-618

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Date 9/10/86

oject No. E-16-632 School/~~XXX~~ AE

cludes Subproject No.(s) N/A

oject Director(s) B. T. Zinn GTRC / ~~GIT~~

onsor AFOSR Bolling AFB, DC

le Investigation of the Flame - Acoustic Wave Interaction During Axial Solid Rocket Instabilities

ective Completion Date: 1/31/86 (Performance) (Reports)

ant/Contract Closeout Actions Remaining:

- [ ] None
- [X] Final Invoice or Final Fiscal Report
- [ ] Closing Documents
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AFOSR INTERIM SCIENTIFIC REPORT

on

INVESTIGATION OF THE FLAME-ACOUSTIC WAVE INTERACTION DURING AXIAL SOLID ROCKET INSTABILITIES

Prepared for

Air Force Office of Scientific Research
Aerospace Sciences Directorate
Bolling Air Force Base

Co-Principal Investigators

Ben T. Zinn
Brady R. Daniel

School of Aerospace Engineering
Georgia Institute of Technology
Atlanta, Georgia 30332

Approved for public release; distribution unlimited
Grant No. AFOSR-84-0082   April, 1985

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7. AUTHOR(s) Ben T. Zinn and Brady R. Daniel		8. CONTRACT OR GRANT NUMBER(s) AFOSR-84-0082
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19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Solid Rocket Instabilities, Flame- Acoustic Interactions, Flame Driving

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The primary objective of this study is the determination of the fundamental mechanisms responsible for the driving of axial instabilities by solid propellant flames. During the reporting period, the behavior of a premixed flame stabilized on the side wall of a duct in the presence of an axial acoustic field has been investigated both theoretically and experimentally. The developed model solutions show that driving occurs due to the combustion process heat addition while outside the reaction zone the waves are damped by viscous processes. This damping

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20. Abstract (cont'd)

increases as the thickness of the acoustic boundary layer increases. Experimental facilities for studying oscillating duct flows in the presence and absence of flames were developed. The cold flow studies verified the presence of an excess velocity region within the acoustic boundary layer (i.e., the Richardson Effect) and the dependence of the boundary layer thickness upon the frequency and wall injection velocity. The reactive flow studies showed that the behavior of the flame depends upon its location relative to the standing acoustic wave. When the flame was positioned next to a velocity antinode, unexpected instabilities appeared on its surface eventually resulting in severe flame distortion. Also, the measured C-C and C-H radiation signals were periodic and they oscillated with the same frequency as the acoustic wave.

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ABSTRACT

The primary objective of this study is the determination of the fundamental mechanisms responsible for the driving of axial instabilities by solid propellant flames. During the reporting period, the behavior of a premixed flame stabilized on the side wall of a duct in the presence of an axial acoustic field has been investigated both theoretically and experimentally. The developed model solutions show that driving occurs due to the combustion process heat addition while outside the reaction zone the waves are damped by viscous processes. This damping increases as the thickness of the acoustic boundary layer increases. Experimental facilities for studying oscillating duct flows in the presence and absence of flames were developed. The cold flow studies verified the presence of an excess velocity region within the acoustic boundary layer (i.e., the Richardson Effect) and the dependence of the boundary layer thickness upon the frequency and wall injection velocity. The reactive flow studies showed that the behavior of the flame depends upon its location relative to the standing acoustic wave. When the flame was positioned next to a velocity antinode, unexpected instabilities appeared on its surface eventually resulting in severe flame distortion. Also, the measured C-C and C-H radiation signals were periodic and they oscillated with the same frequency as the acoustic wave.

INTRODUCTION

At present the mechanisms which control the burn rates of solid propellants in unstable rocket motors are not clearly understood. These mechanisms involve solid and gas phase chemical reactions and heat, momentum and mass transfer and they generally occur within extremely thin regions (i.e., of the order tens of microns). Consequently, practically no experimental studies of these combustion processes have been undertaken to date, and all efforts in this area were confined to the development of theoretical models whose validity is open to question.

The objectives of this research program are:

(1) The determination of the characteristics of solid propellant gas flames in unstable solid propellant rocket motors; and

(2) The determination of the validity of state of the art solid propellant combustion response models.

The above are problems of much practical interest because it is well known that the interaction of the solid propellant flames with the flow oscillations is responsible for the driving of instabilities in rocket motors. Consequently, developing an understanding of the fundamental processes which control this interaction may lead to the development of practical solutions for reducing the driving provided by solid propellant flames. Furthermore, it is believed that the development of a fundamental understanding of oscillatory flames will also improve existing capabilities to deal with other oscillatory flame phenomena, such as those encountered in unstable ramjets, pulsejets, and pulsating combustors.

To gain an understanding of oscillatory flames and their interaction with acoustic fields, the behavior of a premixed flame attached to the side wall of a duct with an axial acoustic oscillation (see Fig. 1) has been investigated during the reporting period. This flame was chosen for this study because it eliminated difficulties associated with diffusion processes while providing the investigator with a flame which possesses many of the features of actual propellant flames. Furthermore, such flames are amenable to experimental probing and they can be modelled using approaches similar to those utilized in solid propellant studies. By comparing the experimental and theoretical results this program will attempt to answer the following questions:

1. What features of the flame (e.g., maximum flame temperature, heat transfer to the propellant surface, rate and spatial distribution of the heat release, possible presence of oscillating vortices and so on) contributes the most to flame driving/damping of core flow acoustic oscillations, and

2. Are state of the art models of unsteady solid propellant flames capable of predicting the characteristics of such or similar flames under conditions simulating those encountered in unstable solid propellant rocket motors.

RESEARCH ACCOMPLISHMENTS

Efforts during the reporting period consisted of experimental and theoretical investigations of the interaction between the core flow oscillations and the flame shown in Fig. 1. The theoretical study solved the acoustic boundary layer equations in the presence and absence of chemical reactions. The solutions were required to satisfy an acoustic admittance boundary condition at the porous duct wall and boundary conditions imposed by the core flow acoustic oscillations at the boundary layer edge. The developed model differed from previous investigations of this problem (e.g., see Ref. 1) by the retention of all terms proportional to $\partial \bar{u}/\partial x$ in the conservation equations as it was felt that the velocity shear is not negligible within the boundary layer region. Comparisons between the predictions of the reactive and nonreactive models and the predictions of previous studies are expected to provide information about the effects of the mean flow shear and the chemical reactions upon the investigated phenomenon.

The following were predicted by the nonreactive model:

1. The damping provided by the wall region is proportional to the acoustic boundary layer thickness. The latter increases with increasing injection velocity at the porous wall and decreasing frequency.

2. A region of excess velocity, where the magnitude of axial acoustic velocity is larger than the corresponding velocity outside the acoustic boundary layer, exists within the acoustic boundary layer in

the presence and absence of flow injection through the porous wall. This corresponds to the well known Richardson Effect which had been discovered earlier (2) for oscillatory flows next to solid walls.

3. The developed cold flow model was used to predict the experimental trends observed in the studies of Hersh and Walker (3) investigated flow turning losses under AFRPL support. The model predictions were in agreement with the data measured in experiments conducted under conditions consistent with the model assumptions. This agreement strongly suggests that the so-called flow turning losses are due to viscous losses in the acoustic boundary layer.

Subsequent investigations with the reactive acoustic boundary model provided the following predictions:

1. The effect of mean flow shear is important near the acoustic velocity antinode where the magnitude of $\partial p'/\partial x$ is significant. Comparisons of the predictions of the present model with those of Ref.1 revealed that the two deviate considerably as the velocity antinode region is approached.

2. The model predicted the behavior of the dependent variables across the acoustic boundary layer under different operating conditions (e. g., see Fig. 2); predictions which will be checked in experimental phase of this program. Figure 2 describes the characteristics of both the steady flame and the acoustic boundary

layer. Significantly, v_r' which is a measure of the acoustic boundary layer driving increases in magnitude in the region where the reaction rate $\bar{w}q$ is nonzero and both quantities have their maxima at the same position. This result clearly shows that the driving is caused by the heat addition due to the combustion process. The observed decrease in v_r' beyond the maximum point is due to viscous effects, indicating that in this region viscous effects dominate the driving by the combustion process.

3. The model also predicted the presence of periodic vortex sheets within the flame region. This result is not surprising if one considers the vorticity equation

$$\frac{d\vec{\xi}}{dt} + \vec{\xi}(\vec{\nabla}\cdot\vec{v}) = \vec{\xi}\cdot\vec{\nabla}\vec{v} + (\vec{\nabla}\rho \times \vec{\nabla}p)/\rho^2 \qquad (1)$$

which shows that nonparallel pressure and density gradients (i.e., when $\vec{\nabla}\rho \times \vec{\nabla}p/\rho^2 \neq 0$) will produce vorticity. This term is indeed nonzero inside the investigated flame region as the presence of the flame creates a density gradient in the y direction and the imposed core flow acoustic pressure oscillation establisheds a nonzero, time dependent pressure gradient in the axial direction. These vortex sheets merit further study as depending upon the magnitude of their velocity jump they may experience Kelvin-Helmholtz type instabilities which may drastically change the character of the flow in the flame region.

The experimental phase of this program consisted of both cold and hot flow studies. The cold flow studies were conducted in a round porous tube closed at one end and connected through a valve to a vacuum chamber at the other end. A standing acoustic wave of desired frequency and amplitude was established in the tube by means of an acoustic driver and the velocity field in the vicinity of the wall was measured with a hot wire. The measured data was in good agreement with the predictions of the developed model. Specifically, both showed the existence of a Richardson layer with the velocity peaks occurring in nearly the same location and both showed that the thickness of the acoustic boundary layer increases as the magnitude of the injection velocity at the wall increases.

The experimental reactive flow studies included the development of a flat flame burner which was utilized to optimize the fuel/air mixing processes used in the preparation of a homogeneous combustible mixture; to investigate the stabilization of the flat flame on top of a porous ceramic plate; to investigate the seeding of the flame through the porous burner face which will be required in future flame LDV studies; and to investigate the potential use of the inclined slit technique in the determination of the steady temperature distribution in a direction normal to the flat flame surface. All of the developed solutions have been and/or will be utilized in the proposed experimental studies.

A schematic of the developed experimental setup is shown in Fig. 3. The acoustic drivers can be used to excite a standing acoustic wave of desired properties in the tube and capabilities exist for positioning the flat flame on any desired location on the standing acoustic wave. Experiments can be conducted in the presence or absence of a hot mean flow. Capabilities have also been developed for shadowgraphy/Schlieren high speed cine visualization of the flow, flame radiation measurements and acoustic pressure and steady flame temperature measurements.

High speed cine flame visualizations at various locations on the standing acoustic wave revealed the following:

1. In regions away from a velocity antinode, the flame remains essentially flat and it is displaced up and down relative to the wall. The time dependence of the flame position oscillations were measured and correlated with the corresponding pressure oscillations. The results will be compared with the model predictions.

2. When the flame is positioned near a velocity antinode, small wavelets (i.e., instabilities) which grow in amplitude and propagate along the flame are observed. These wavelets result in flame distortion. They were not predicted by the developed model nor were they observed before under similar experimental conditions. The presence of these wavelets or instabilities may be significant and they will be further investigated in the future.

Flame radiation measurements revealed the existence of periodic radiation whose frequency was the same as that of the excited acoustic wave. Near future studies will investigate the phase relationship between the radiation and pressue oscillations in an effort to determine whether Rayleigh's criterion is satisfied by the investigated flames.

Finally, the flame visualization studies also showed that the flat flame stabilized farther away from the side wall as the amplitude of the oscillation increased. This could be due to nonlinear flow effects and it merits further study.

REFERENCES

1. Flandro, G. A., "Nonlinear Time Dependent Combustion of a Solid Rocket Propellant," CPIA Publication No. 366, Vol. II, pp. 111-122, 1982.

2. Temkin, S., "Elements of Acoustics," John Wiley & Sons,, New York, 1981.

3. Hersh, A. S. and Walker, B., "Experimental Investigation of Rocket Motor Flow-Turning Acoustic Losses," AFRPL Interim Report No. TR-84-009, May 1984.

PUBLICATIONS

1. Salikuddin, M., Daniel, B. R. and Zinn, B. T., "Experimental Observations of the Dependence of Impedance Tube Behavior upon Gas Phase Losses and Propellant Self-Noise", Journal of Sound & Vibration, 93(2), 1984.

2. Hegde, U. G., Chen, F. L., and Zinn, B. T., "Investigations of Reactive and Non Reactive Acoustic Boundary Layers on Porous Walled Ducts", Proceedings of the 21st JANNAF Combustion Meeting, Oct. 1984. Also, AIAA Paper No. 85-0235.

3. Narayanaswami, L., Daniel, B. R. and Zinn, B. T., "Investigation of the Characteristics of the Velocity-Coupled Response Functions of Solid Propellants", Proceedings of the 21st JANNAF Combustion Meeting, October 1984.

4. Hegde, U. G., Chen, F. L. and Zinn, B. T., "Investigations of the Acoustic Boundary Layer in Porous Walled Ducts with Flow". AIAA Paper No. 85-0078, January 1985.

5. Narayanaswami, L. L. and Zinn, B. T., "An Improved Approach for Determining the Pressure-Coupled Responses of Solid Propellants Using the Impedance Tube Technique". In preparation.

6. Narayanaswami, L. L. and Zinn, B. T., "Effect of Aluminum Addition to Solid Propellants Upon Gas Phase Damping: A Comparison Between Theory and Experiment". In preparation.

7. Hegde, U. G., Chen F. L. and Zinn, B. T., "Investigations of the Acoustic Boundary Layer in Porous Walled Ducts with Flow". In preparation.

8. Hegde, U. G. and Zinn, B. T., "The Acoustic Boundary Layer in Porous Walled Ducts with a Reacting Flow". In preparation.

PROFESSIONAL PERSONNEL

The following individuals contributed to the research effort described in this section:

Dr. Ben T. Zinn, Regents' Professor of Aerospace Engineering

Mr. Brady R. Daniel, Senior Research Engineer

Dr. Jechiel I. Jagoda, Assistant Professor.

Dr. Uday G. Hegde, Post-Doctoral Fellow

Mr. Julian Chen, Visiting Scholar from Northwestern Polytechnic Institute, Xian, People's Republic of China.

Mr. Subramanian V. Sankar, Ph.D Student.

Also, Mr. Lakshmanan L. Narayanaswami completed his Ph.D research entitled:

"Investigation of the Pressure-and Velocity-Coupled Responses of Solid Propellants using the Impedance Tube Technique"

in July 1984. The majority of this research was supported by the AFOSR Grant which preceded the present program.

PRESENTATIONS

1. "Investigations of Reactive and Non Reactive Acoustic Boundary Layers on Porous Walled Ducts," presented at the 21st JANNAF Combustion Meeting, Laurel, MD, October 1-4, 1984.

2. "Investigation of the Characteristics of the Velocity-Coupled Response Functions of Solid Propellants," presented at the 21st JANNAF Combustion Meeting, Laurel, MD, October 1-4, 1984.

3. "Investigations of the Acoustic Boundary Layer in Porous Walled Ducts with Flow," presented at the AIAA 23rd Aerospace Sciences Meeting in Reno, Nevada, January 14-17, 1985.

4. "Investigation of the Characteristics of the Velocity-Coupled Response Functions of Solid Propellants," presented at the AIAA 23rd Aerospace Sciences Meeting in Reno, Nevada, January 14-17, 1985.

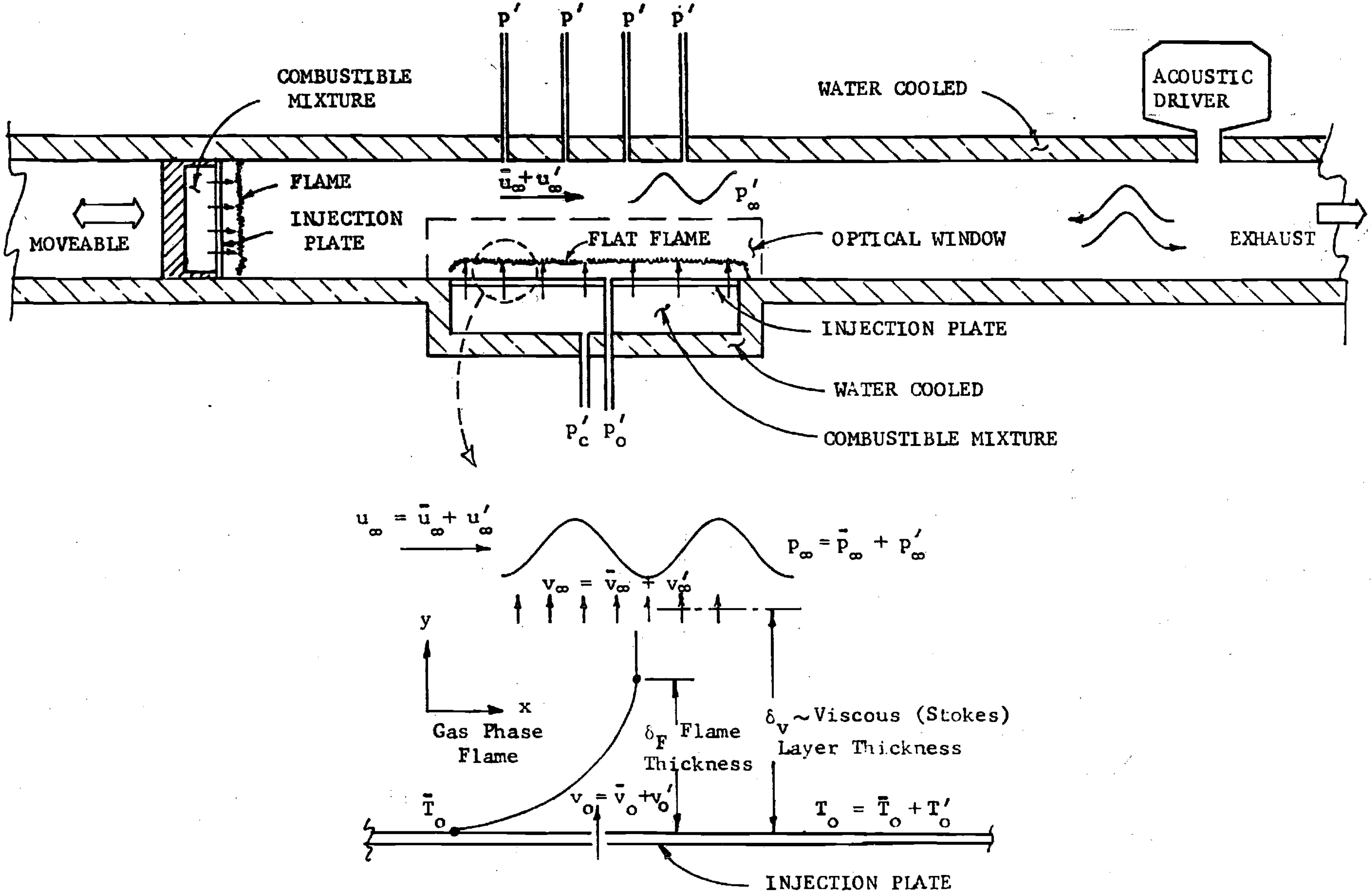

Figure 1. A Schematic of the Experimental Setup (above) and the Anticipated Flame Structure (below).

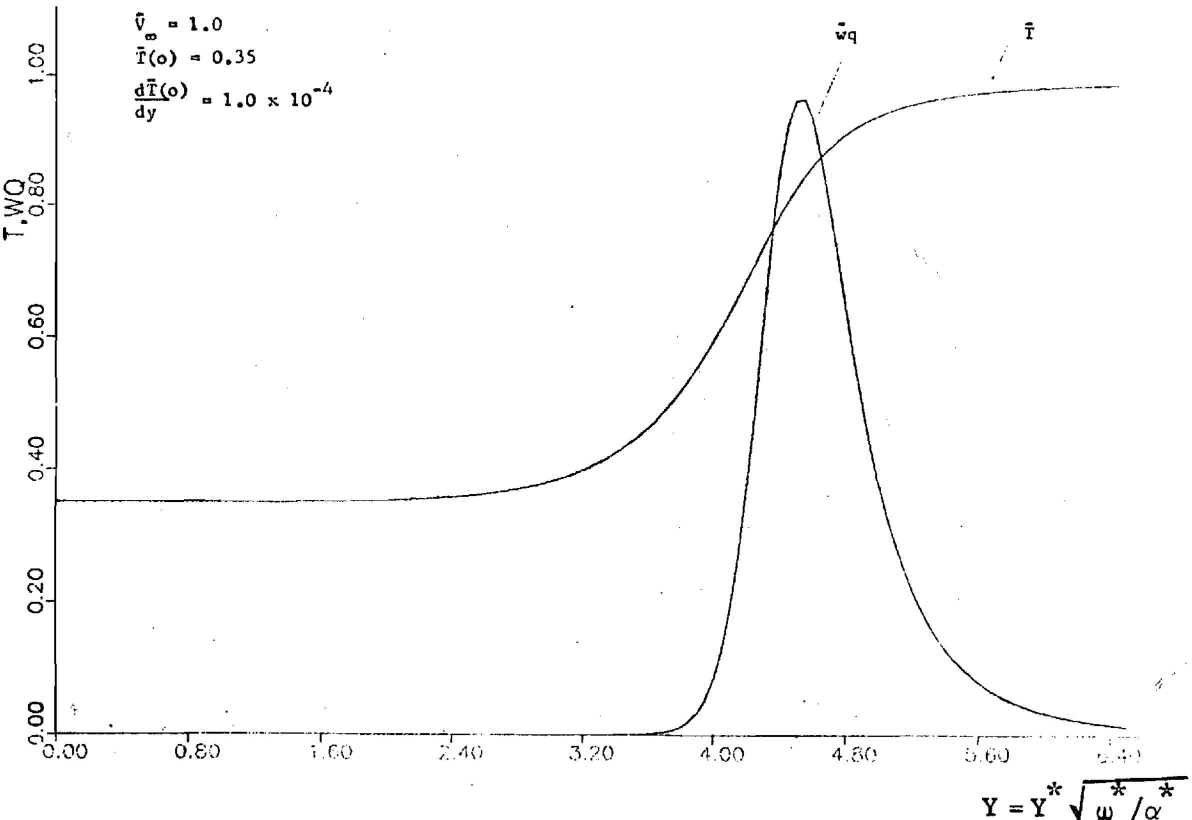

Figure (2-a). Predicted Steady State Temperature and Heat Release ($w\bar{q}$) Rate Distributions in the Flame Region.

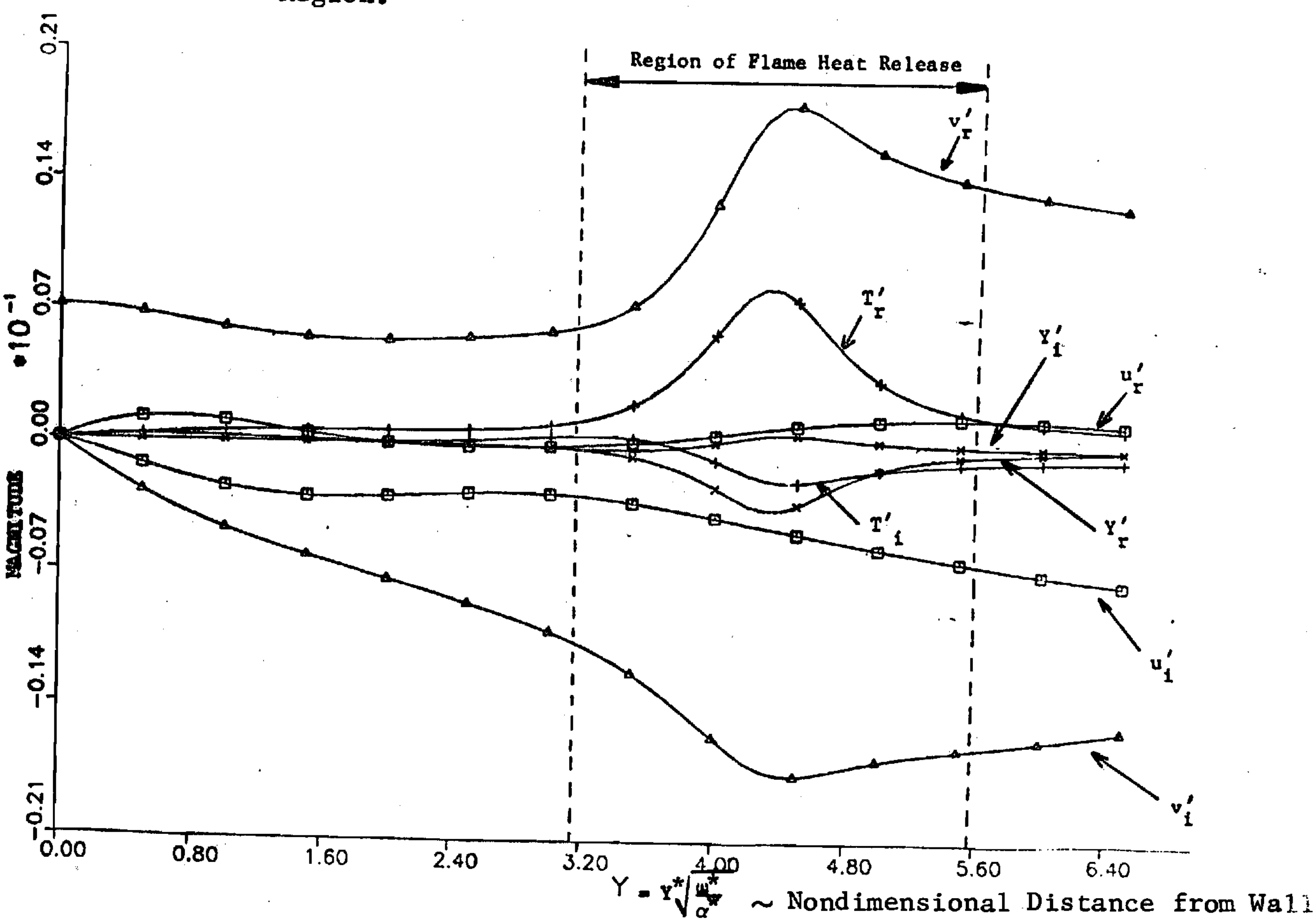

Figure (2-b). Predicted Oscillatory Solutions in the Flame Region; $\sqrt{\alpha^*/\omega^*}$ is the Thickness of the Stokes Layer

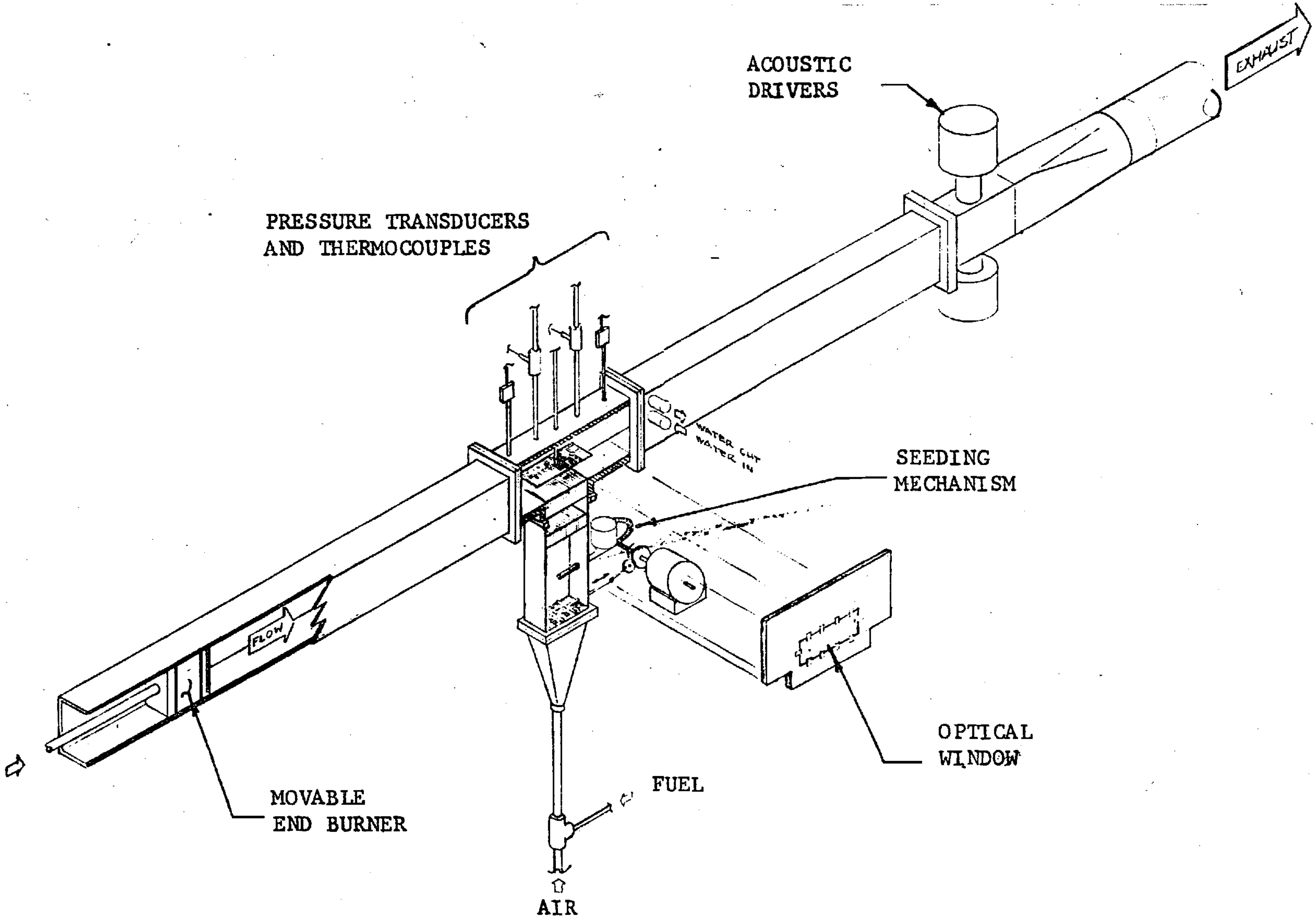

Figure 3. An Isometric of the Developed Experimental Setup.

E-16-632

AFOSR ANNUAL TECHNICAL REPORT

INVESTIGATION OF THE FLAME-ACOUSTIC WAVE INTERACTION DURING AXIAL SOLID ROCKET INSTABILITIES

Co-Principal Investigators

Ben T. Zinn
Brady R. Daniel

Prepared for

Air Force Office of Scientific Research
Aerospace Sciences Directorate
Bolling Air Force Base

Under

Grant No. AFOSR-84-0082

March 1986

GEORGIA INSTITUTE OF TECHNOLOGY
A UNIT OF THE UNIVERSITY SYSTEM OF GEORGIA
SCHOOL OF AEROSPACE ENGINEERING
ATLANTA, GEORGIA 30332

1986

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INTRODUCTION

This research program is concerned with the determination of the characteristics of the gas phase combustion processes of solid propellants burning in unstable rocket motors. This problem is of much interest because it is well known that the response of the solid propellant combustion process to the flow oscillations is responsible for providing the energy required for the initiation and maintenance of instabilities inside the rocket motors. Consequently, acquiring an understanding of the processes which control the response of solid propellant combustion processes to flow oscillations may lead to the development of practical solutions for reducing the occurrence of instabilities in solid propellant rocket motors.

At present the mechanisms which control the burn rates of solid propellants in unstable rocket motors are not clearly understood. These mechanisms involve solid and gas phase chemical reactions, complex, multidimensional heat, momentum and mass transfer processes and they generally occur within extremely thin regions (i.e., of the order of tens of microns). Consequently, no detailed experimental probing of oscillatory solid propellant flames have been undertaken to date, and all efforts in this area were confined to the development of theoretical models whose validity is yet to be confirmed. The objectives of this research program are:

1) The determination of the characteristics of solid propellant gas phase flames in unstable solid propellant rocket motor environments; and

(2) The determination of the validity of state-of-the-art solid propellant combustion response models.

Since actual solid propellant flames could not be used in the present study because of their extremely small dimensions, the behavior of a premixed flame, stabilized at some distance from the side wall of a duct with an axial acoustic oscillation, has been investigated instead during the period of reporting in an effort to gain the needed understanding of the interaction of oscillatory gas phase flames and axial acoustic fields. This flame was chosen for this study because it eliminated difficulties associated with diffusion processes while providing the investigators with a flame which possesses some important features of actual solid propellant flames. Furthermore, such flames are amenable to experimental probing and they can be modelled using approaches similar to those utilized in solid propellant studies. By comparing the experimental and theoretical results this program will attempt to answer the following questions:

(1) Are state-of-the-art models of unsteady solid propellant flames capable of predicting the characteristics of such or similar flames under conditions simulating those encountered in unstable solid propellant rocket motors?

(2) What acoustic conditions result in optimum flame driving?

(3) What mechanisms (e.g., oscillatory heat transfer to the propellant surface, possible presence of oscillating vortices and so on) are responsible for flame driving?

RESEARCH ACCOMPLISHMENTS

Research during the reporting period was conducted in the previously developed experimental setup (Fig. 1) and it involved extensive experimental investigation of the interaction between the core flow oscillations and the stabilized premixed flames.

Flame radiation from C-C and C-H species were measured for flames located at various points on the standing acoustic wave in the duct. The concentrations of these species provide a measure of the reaction rate and, hence, the heat release rate. These studies revealed the following:

(1) When the flame is located away from an acoustic pressure minima, its radiation oscillates with the same frequency as that of the excited acoustic wave.

(2) When the flame is located at an acoustic pressure minimum, oscillatory radiation is either absent or too weak to be detected by the photomultiplier. At this location small wavelets which grow in amplitude and propagate along the flame are observed and this phenomena has been reported previously. It is possible that these wavelets drive or damp acoustic oscillations as they move away from this region.

(3) The magnitude of the radiation oscillation increases as the pressure amplitude increases.

(4) The phase difference between the radiation oscillations and pressure oscillations, which determine whether the flame drives or damps the oscillations depends on the flame speed, the injection velocity at the burner surface, the surface temperature of the ceramic matrix and the driven acoustic frequency, see Figs. 2 and 3. It does not depend on the location of the flame on the standing acoustic wave.

(5) When the flame is stabilized at some distance from the burner surface the phase difference between the radiation and pressure oscillations is such that Rayleigh's criterion for driving acoustic oscillations is satisfied for all frequencies; that is,

$$\int_{\text{cycle}} p' \, Q' \, dt > 0$$

where p' is the pressure and Q' is the heat release rate, or the measured time dependent radiation.

(6) When the flame is stabilized on the ceramic matrix surface Rayleigh's criterion is not satisfied for all frequencies. In these cases the magnitudes of the radiation oscillations are very much greater than those obtained when the flame is stabilized at some distance from the burner.

(7) The flame radiation oscillations and the flame displacement oscillations are 180^{o} out of phase, implying that the radiation from the flame is a maximum when the flame is closest to the burner surface and a minimum when the flame is farthest away from the burner.

(8) Spontaneous radiation oscillations occurred for certain fuel concentrations. The flame speeds for these cases were always greater than the combustible mixture injection velocity at the burner surface (i.e., in these cases the flames stabilized on the ceramic matrix of the burner).

The measured radiation data strongly suggests that oscillatory heat transfer to the propellant surface, which is associated with the observed flame oscillations, plays an important role in the mechanism responsible for the driving of axial instabilities.

One of the aims of this research program is to examine the validity of solid propellant combustion response models by modelling the experimental flame using state-of-the-art approaches and then comparing the predicted and measured response of the investigated flames to imposed core flow oscillations. For this purpose, the theoretical model requires, as one of its inputs, the steady state temperature distribution through the flame. The optical method of temperature determination, known as the "inclined-slit method" [1], was used to determine the temperature distribution. This technique makes use of the fact that a light beam incident on a region of a gas with a temperature gradient and, thus, a refractive index gradient normal to the beam, will be deflected by an amount proportional to the gradient. A schematic of the experimental setup used is shown in Fig. 4 and Fig. 5 shows the steady state temperature distribution obtained by this method for a flame with a fuel concentration of 2.3%.

In order to check the validity of the temperature distribution obtained from the inclined-slit measurement technique, the maximum temperature obtained from this method was compared with the maximum temperatures obtained by using both coated and uncoated, 0.005" diameter Pt-Pt/13% Rh thermocouples. The exposed portion of the thermocouple was coated with an eutectic mixture of 15% beryllium oxide in yittrium oxide, following the method of Kent [2]. The thermocouples were also modeled to correct for errors resulting from radiative, convective and conductive heat transfer [3]. The maximum temperature obtained by using the inclined-slit method was 1587K and that obtained using the "coated" thermocouple, after correction, was 1567K. This excellent agreement between these two methods strongly suggests that the inclined-slit technique provided the correct steady state temperature distribution within the flame.

The acoustic admittance of the side wall burner assembly is another input required by the theoretical model. The admittance of the burner system was measured by the conventional "standing wave" technique [4].

Theoretical efforts during the reporting period included calculation of the thermodynamic and transport properties of mixtures of propane (fuel) with air [5,6]. The assumption of constant composition for all temperatures was made. The properties were calculated for temperatures ranging from 300K to 2500K in steps of 50K. Sixth degree polynomials were generated (using least square approximations) to fit each of the thermodynamic and transport properties.

The developed theoretical model was also used to investigate the characteristics of the unsteady flame. Specifically, the model was used to predict the time dependence of the flame position and its reaction rate; data which were also measured in the experimental phase of the program. Since not all the model input data was available, some assumed flame data were used in the model predictions. This study revealed the following:

(1) No reaction rate fluctuations occur at acoustic pressure nodes.

(2) The phase difference between the reaction rate oscillations and the pressure oscillations is independent of the amplitude of the pressure oscillation.

(3) The phase difference between the reaction rate oscillation and pressure oscillation is independent of the location of the flame in the standing acoustic wave (except at a pressure node).

(4) If the location of the maximum reaction rate is assumed to be the location of the flame, then, the phase difference between the

reaction rate oscillation and flame displacement oscillation is 180^{o}, see Fig. 6.

(5) The flame displacement increases as the pressure amplitude increases.

(6) When pressure amplitude is large the reaction rate becomes negative. This, probably, implies non-existence of the flame at the higher pressure amplitudes or, better, that the linear analysis is no longer applicable.

These preliminary theoretical predictions are most encouraging because they are in excellent qualitative agreement with observations made during the experimental phase of this program. Another comparison between the model predictions and measured data will be performed later on during the current reporting period when all of the needed model input data becomes available.

REFERENCES

1. Burgoyne, J. H. and Weinberg, F. J., "Determination of the Distribution of Some Parameters Across the Combustion Zone of a Flat Flame," J. Proc. Royal Soc., A224, p. 286, 1954.

2. Kent, N. H., "A Non-Catalytic Coating for Platinum-Rhodium Thermocouples," Combustion and Flame, Vol. 14, p. 279, 1970.

3. Scadron, M. D. and Warshawsky, I., "Experimental Determination of Time Constants and Nusselt Numbers for Bare-Wire Thermocouples in High-Velocity Air Streams and Analytic Approximation of Conduction and Radiation Errors," NACA Technical Note 2599, Jan. 1952.

4. Pierce, A. D., "Acoustics: An Introduction to its Physical Principles and Applications," McGraw-Hill Book Co., 1981.

5. Gordon, S., "Thermodynamic and Transport Properties of Hydrocarbons with Air," NASA Technical paper 1906, July 1982.

6. Svelha, R. A. and McBride, B. J., "Fortran IV Computer Program for Calculation of Thermodynamic and Transport Properties of Complex Chemical Systems," NASA Technical Note 0-7056, Jan. 1973.

PUBLICATIONS

1. Sankar, S. V., Jagoda, J. I., Daniel, B. R. and Zinn, B. T., "Driving of Axial Oscillations by Simulated Solid Propellant Flames," Proceedings of the 22nd JANNAF Combustion Meeting, Oct. 1985.

2. Sankar, S. V., Jagoda, J. I., Daniel, B. R. and Zinn, B. T., "Flame-Acoustic Wave Interaction During Axial Solid Rocket Instabilities," AIAA Paper No. 86-0532.

PROFESSIONAL PERSONNEL

The following individuals contributed to the research effort described in this section:

Dr. Ben T. Zinn, Regents' Professor of Aerospace Engineering

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Dr. Jechiel I. Jagoda, Associate Professor

Mr. Subramanian V. Sankar, Ph.D Student

PRESENTATIONS

1. "Driving of Axial Oscillations by Simulated Solid Propellant Flames," presented at the 22nd JANNAF Combustion Meeting, Pasadena, Ca., Oct. 7-11, 1985.

2. "Flame-Acoustic Wave Interaction During Axial Solid Rocket Instabilities," presented at the AIAA 24th Aerospace Sciences Meeting in Reno, Nevada, January 7-9, 1986.

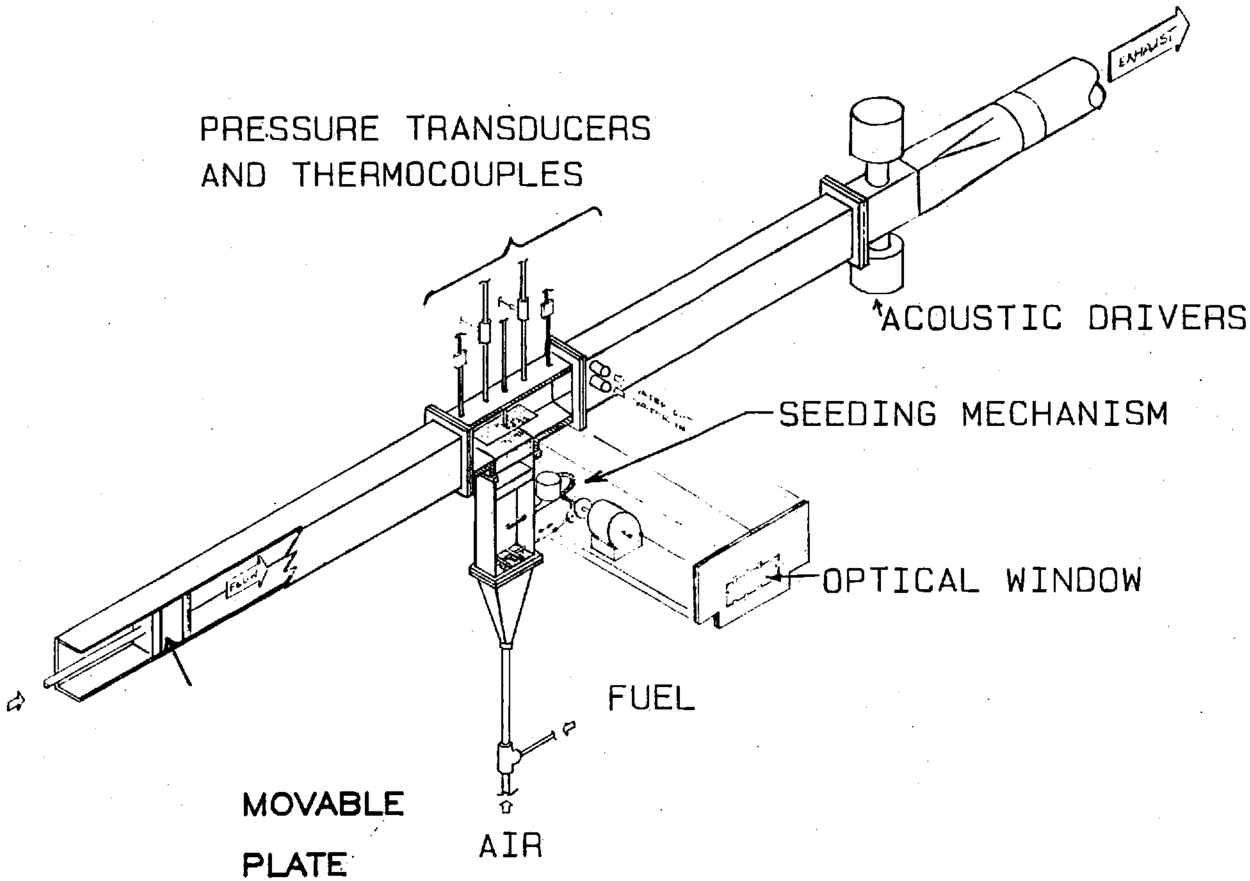


Figure 1. Schematic of developed experimental setup.

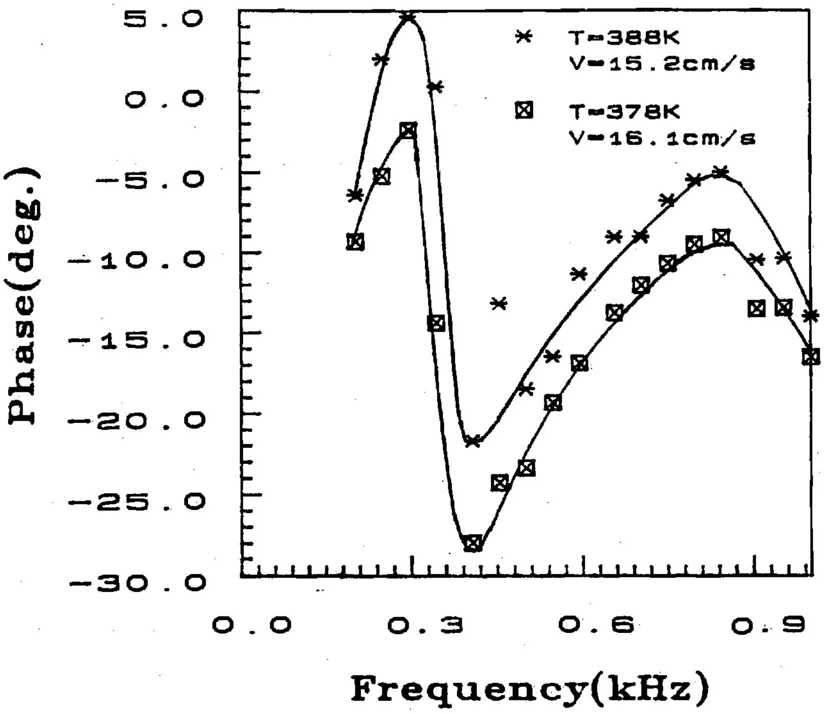


Figure 2. Phase differences between radiation oscillation and pressure oscillation for flames stabilized some distance away from the ceramic matrix surface.

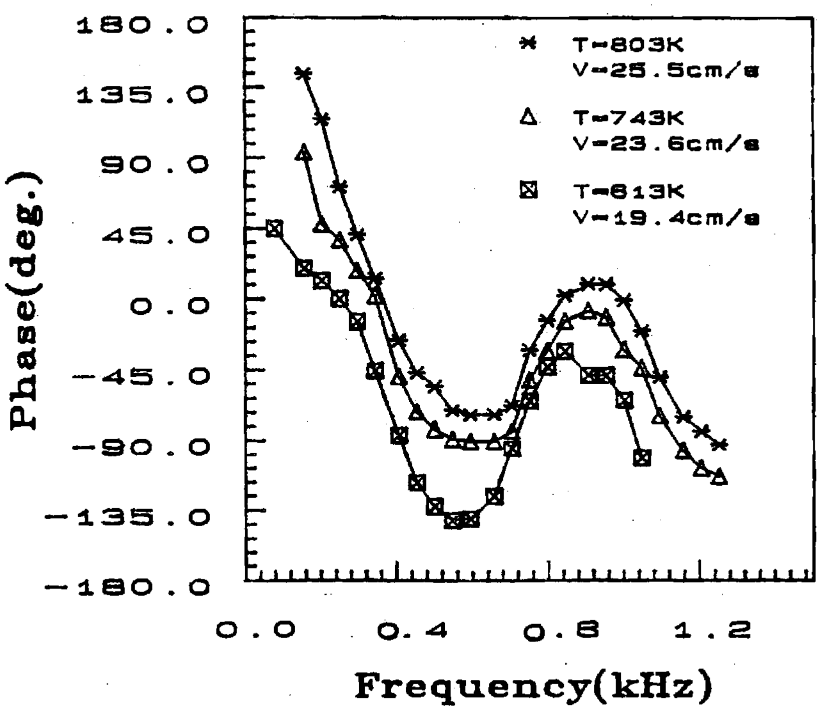
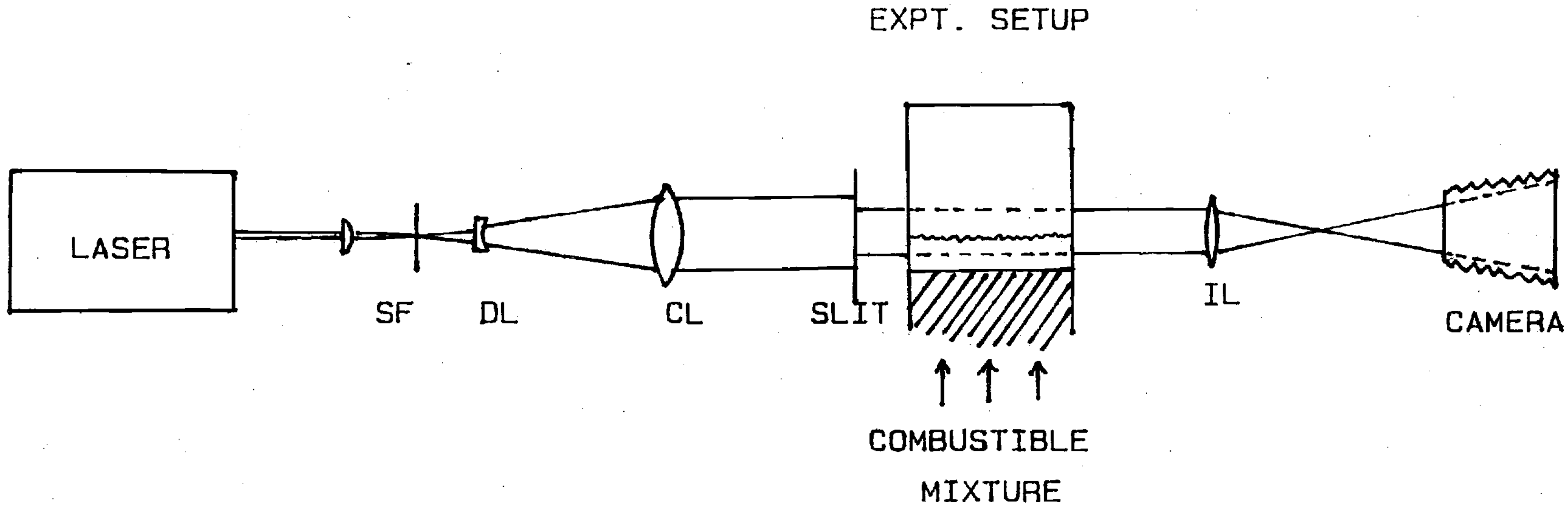


Figure 3. Phase differences between radiation oscillation and pressure oscillation for flames stabilized on the ceramic matrix surface.



SF SPATIAL FILTER

DL DIVERGING LENS

CL COLLIMATING LENS

IL IMAGING LENS

Figure 4. Schematic of inclined-slit setup.

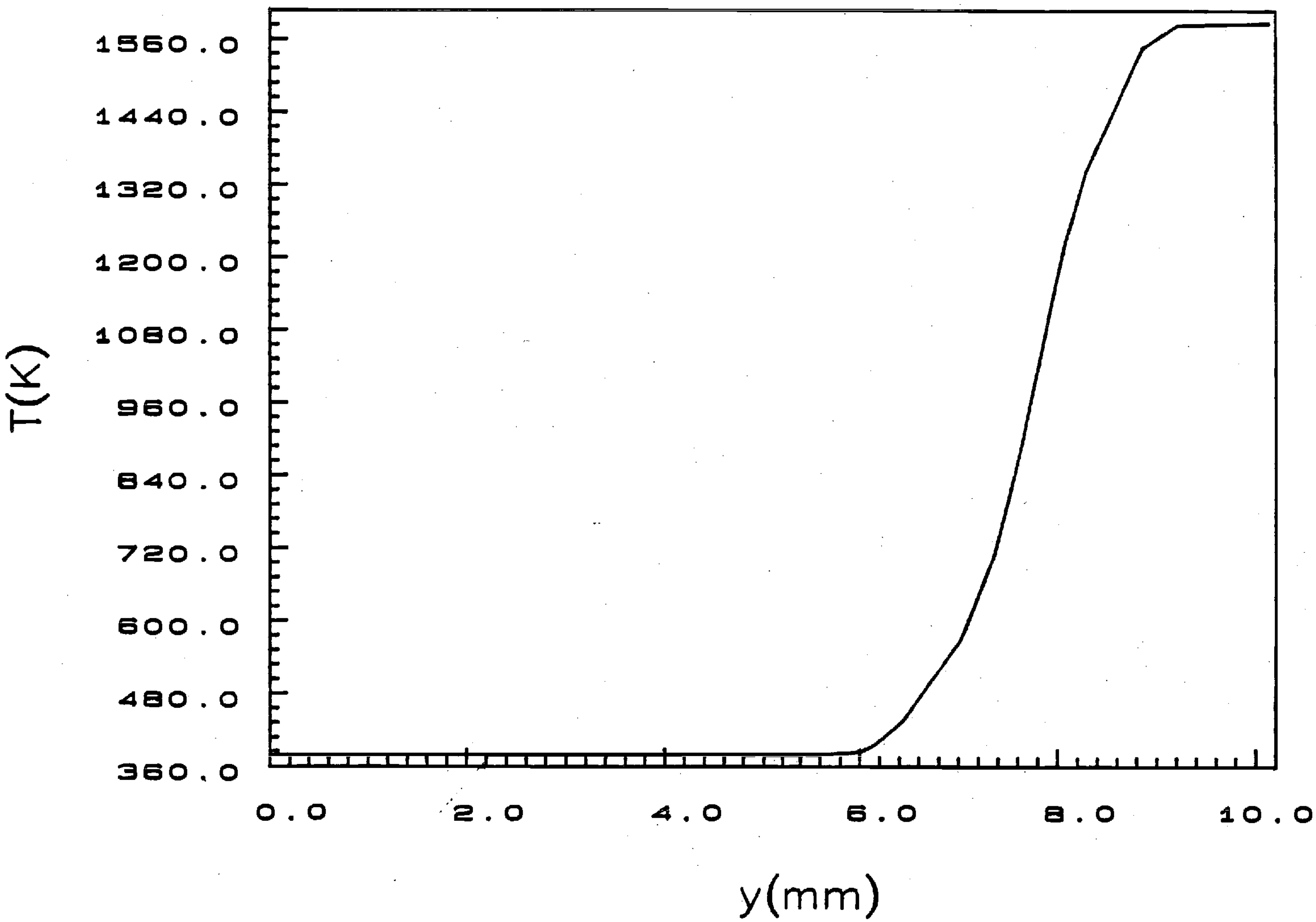


Figure 5. Measured steady state temperature distribution.

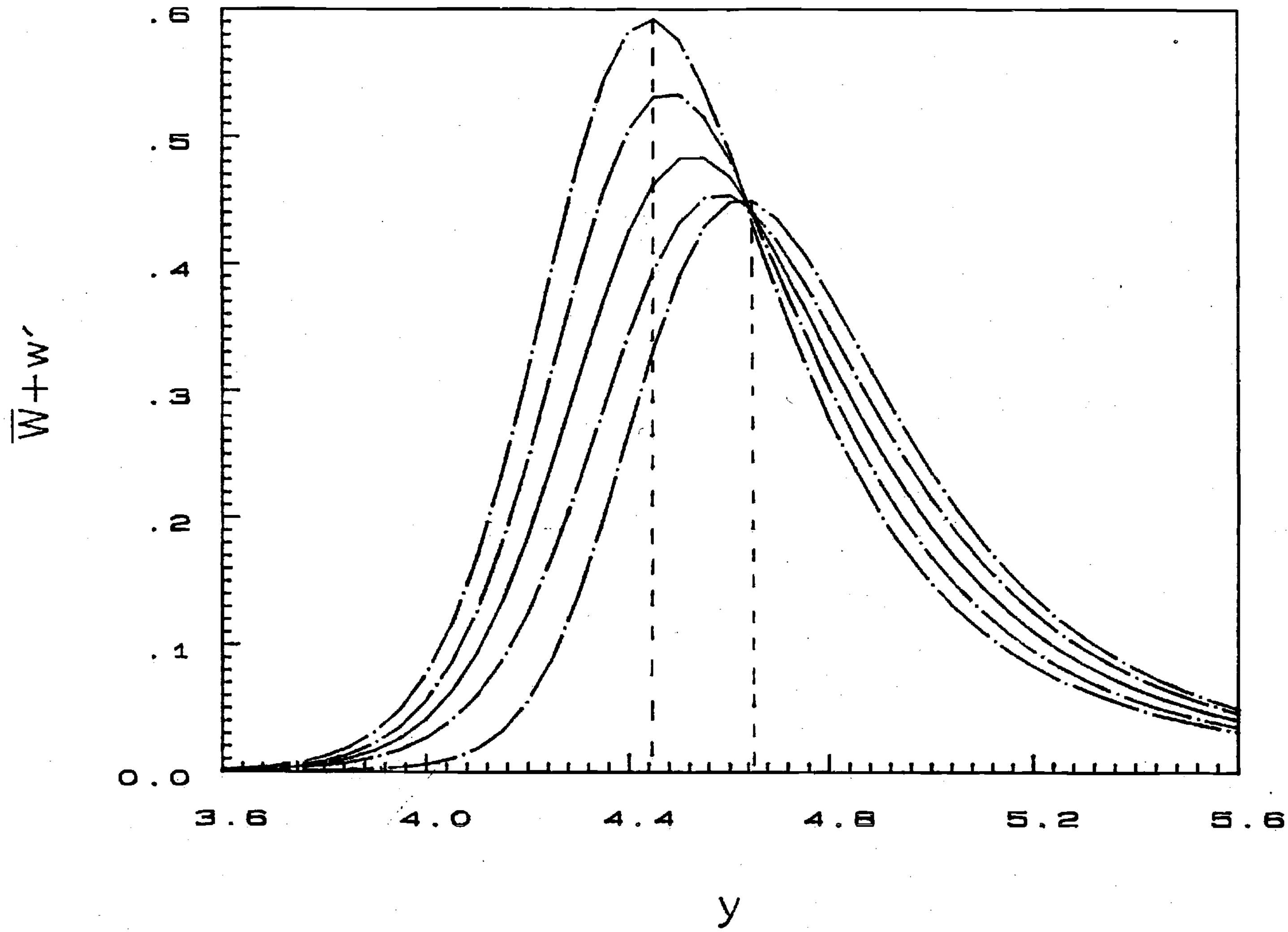


Figure 6. Reaction rate distributions at different instances during one cycle of pressure oscillation - obtained from model using simulated data.